Evaluation of Energy Storage Solutions for the Hyperloop System*

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Abstract

This report is an evaluation of four different potential technologies to be used as an on-board energy storage device in Elon Musk's proposed Hyperloop transportation system. The four options are lithium iron phosphate batteries, lead-acid batteries, the compressed air energy storage device, Lightsail, and the pumped heat energy storage device developed by Isentropic Ltd. Lithium iron phosphate batteries are the best option, although they do not meet all of the criteria we used to analyze the technologies.

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SUBJECT: Evaluation of Energy Storage Solutions for the Hyperloop System

Introduction

Each day, thousands of people commute between San Francisco and L.A., California. They travel by airplane, train, bus, or car, but none of these solutions provides a safe, quick, and cheap method of transportation. Due to this need, there has been increased interest in finding a technology that fulfills the previous requirements and is both environmentally friendly and feasible to create. The Senate recently approved a project to create a high-speed rail line between the two cities at an estimated $68 billion. The entrepreneur Elon Musk has come up with what he believes to be a better idea, which he calls the hyperloop. The hyperloop would consist of a capsule that would travel down a tube and reduce the time of the trip to a mere 45 minutes. Its primary source of energy would be solar panels, and it would use land near or in the center median of I-5[1]. To determine its feasibility, we focused on an aspect of the hyperloop that Elon Musk did not provide much detail on: the on-board battery. The on-board battery would only have to provide enough energy to power the compressor and capsule systems. We based our research on the passenger-only capsule, which is a bit smaller. Our goal was to determine if technology exists for such a battery and if it does, which would be the most ideal. The type of technology has to fulfill the specifications from Musk's report, including but not limited to criteria such as size, weight, energy output, safety, and cost. We choose to analyze four types of batteries: Lead-acid, Lithium iron phosphate, Lightsail's compressed air storage, and Isentropic's pumped heat energy storage. Based on these, we assessed if there was available technology with the ability to satisfy the specifications for the hyperloop system.

Background/Motivation

We assumed that to fulfill the need of those travelling between L.A. and San Francisco, the hyperloop would have to be created only using technologies available, not theoretical ones. Therefore we looked into

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the two leading types of car batteries as well as newer technologies. The first was the lead-acid battery. This battery was the first type of rechargeable battery developed. It consists of flat lead plates immersed in sulfuric acid electrolytes. The positive lead plate is covered with a paste of lead dioxide and the negative plate is made of sponge lead. The battery discharges by conduction of electrolytes from the negative plate back to the positive plate and charges by removal of electrons from the positive plate to the negative plate by a charging source. Cars use lead-acid batteries for their low cost of purchase and their ability to start motors at a low cost.

Another type of battery present in the industry is the lithium iron phosphate battery. This is a type of lithium-ion battery and it is currently one of the most popular types of rechargeable batteries for electric vehicles. A typical lithium-ion battery consists of an anode, a cathode, and an organic solvent, which acts as the electrolyte. When the battery discharges, lithium ions moves from anode to cathode through the electrolyte, and in reverse order when charging. Partial discharge and relatively low temperature are preferred for durability of Li-ion batteries[2], so it is important to avoid complete discharge and high temperature for our system. Because lithium-ion batteries are commonly used in laptops, phones, and now Tesla automobiles, plenty of information exists on the properties of this technology.

In his report on the hyperloop, Elon Musk gave a suggestion for a technology he believes can satisfy the requirements of an on-board battery. He proposed the new, not yet in production, LightSail process. LightSail is a compressed air energy storage technology that claims to achieve 90% thermodynamic efficiency. The process is based on the concept of capturing the heat generated by compressing air; when the air is compressed, a spray of water captures the heat that is released and stores it in a tank until it can be later converted back to mechanical energy. This process creates very clean energy, as no harmful chemicals are being released and there is no need to recycle or dispose of any dangerous byproducts. The amount of quantitative technical information available about the size, cost, and durability of a LightSail storage device is limited compared to the amount of this information available for our other technologies.

Our final type of battery we researched was Isentropic Energy's Pumped Heat Electricity Storage (PHES) battery. Isentropic is a company that has developed an efficient energy storage solution through packing gravel in tanks and heating them to store energy. The process is claimed to achieve high, nearly reversible levels of efficiency, and uses the reversible Brayton cycle, also known as the First Ericsson Cycle, as a model for their design. This pumped heat energy storage technology has been developed but is currently not used for large-scale operations. Using a technology such as PHES, if it were to fit the criteria, would require an additional step of preparing the technology for large-scale production and installation. Ideally, the technology we would use in the hyperloop would already be in production so that it is only a matter of adjusting the technology to fit the specifications of the hyperloop capsule.

Evaluation Criteria

Since the hyperloop transit system requires energy to be stored on the train car to continue movement, the system requires an appropriate energy storage solution in order to work properly. To select an energy storage device for the hyperloop transit system, we created a set of evaluation criteria. We ranked our criteria in order of importance using a pairwise comparison chart (See Appendix Table 1). In order to have a basis for these criteria, we extracted data from the hyperloop proposal and then researched each technology to find how they compare to these bases.

To even be feasible for the hyperloop system, the selected design must meet certain design constraints, and we selected safety, power output, size, and weight as our evaluation criteria. These four were ranked the highest on the pairwise comparison chart because they determine if the selected design can even be implemented. Cost, durability, energy efficiency, and charge time are the other design criteria, and these were selected to maximize the efficiency of the energy storage system, allowing easier long-term use and fewer storage devices charging between trips.

Safety is a measure of the probability of injury per energy storage device. Our target level is less than 1 in every 10,000 energy storage devices used has a chance of injury. This criterion was considered most important because the device would not be used at all if it posed substantial threats to personnel; however, safety was given little weight on the Pugh scoring matrix for larger spread, as most of the designs have very similar safety standards. Power output is the physical measurement of the device's power. The device

must output 325 kilowatts (or 436 horsepower) for 45 minutes for the hyperloop system to travel from Los Angeles to San Francisco. Size is also a physical measurement, as the passenger-only transportation capsule frontal area where the device would be placed is only 1.4 m^2 (1.35m x 1.1m). If the capsule were enlarged to accommodate a larger energy storage device, this would require an extensive redesign of the entire system, specifically the size of the tube and the air bearings that are used to keep the capsule suspended. Our final constraint is that the storage device should not weigh more than 1,500 kg (or 3,400 lbs.), which is the benchmark set in Elon Musk's hyperloop proposition, in order to maximize energy efficiency and prevent accidents during transit[1].

The cost of the hyperloop, including battery, motor, and coolant, should not exceed than $150,000 per capsule in order to stay competitive with alternative forms of transportation. Cost of the selected design is therefore very important in minimizing the cost of the full capsule. Specifically, the battery cannot exceed $150,000 per capsule and should be minimized in order to leave more money for the motor and coolant. Durability is a measure of how long the selected design can last before it falls below 70% of its maximum charge capacity. The device should be durable for two years, or approximately 3,000 charge cycles. Energy efficiency is a measure of how much energy the selected device can output compared to how much it initially stores. Our device should outputat least6 MW, or about 21% of the energy it initially stores in order to be energy efficient. This criterion is not our top priority because the solar panels output 28 MW of energy, which is considerably more energy than the battery needs to store. Lastly, optimizing charging time would decrease the amount of batteries at each station, as fewer batteries would have to be charged for the next hyperloop capsule to be ready. The battery must be able to charge within 13 hours (382 miles from LA to SF divided by 29 miles per hour for a Tesla Li battery to charge). This is not as important as the other criterion because the storage devices are assumed to readily switch out with a fully charged battery, and can be used for multiple trips if their storage capacity exceeds the energy output needed to power one trip.

Discussion

While evaluating potential energy storage options for the Hyperloop system, our team established key assumptions to make our analysis possible. First, we assumed that the implemented solution would use current available technology. This assumption is critical because research and development could make unconventional options more viable over time. We decided not to consider research and development because doing so would complicate our decision matrices and could lead us to recommend an unfeasible solution.

Our battery calculations for energy efficiency, power output, energy cost, and charge time assumed the use of a 0.1 kWh/kg lithium iron phosphate battery. We linearly scaled up our estimated cost of our batteries by simply multiplying by a scale factor to reach 243 kWh for our energy storage option. We recognize battery cost does not simply scale this way, but an assumption is necessary due to lack of information on the cost of a 243 kWh lithium iron phosphate battery.

Another assumption we made was that our chosen energy storage solution would be easily removed from the capsule to allow immediate replacement by another battery. If the battery were to not be removable, significant time would be spent charging the battery, meaning we would weigh our charge time criteria more heavily. This assumption was based off Elon Musk's suggestion that batteries are changed at each stop on the hyperloop system.

For technologies with limited amounts of information, such as LightSail and Isentropic Energy, we assumed the data gathered from the company producing the technology is accurate and could be currently used as an energy storage solution. Since some of the data has been completed on an experimental level, it may not be reliable once implemented to full scale.

Using a lead-acid battery was the first solution we evaluated. The main advantage of the lead-acid battery is its low cost. A Power-Sonic PS-1270 lead acid battery (12V 7Ah) can be purchased at 15 dollars[3]. We assumed that each time the battery is depleted it would only use 80% of its maximum capacity to account for its degradation over time. If we assume that the discharge efficiency of the lead-acid battery is 80%[4] and the cost can be scaled up according to the energy storage of this lead-acid battery, then the total cost of battery for one capsule is only $68,011. This is much less than the budget allowance as well as the cost of the lithium-ion battery. If we take durability of the battery into consideration, a lead-acid battery can be charged for 300 cycles before the max capacity declines to 80%[5], then the cost of energy storage is

\$0.93/kWh. The main disadvantage of a lead-acid battery is that it has a very low energy-to-weight ratio (approximately 40 watt hours/kg) and a low energy-to-volume cost (approximately 87.5 watt hrs/L)[6]. We calculated the weight of lead-acid battery to supply the power (325 kW) and energy (243.75 kWh) required for the trip. If we use the lead-acid battery in the capsule, the battery needs to be at least 9521 kg and 4.35 m^3. [7] That means that a very heavy and large lead-acid battery would be used in the small space of the capsule. Since our weight criterion aims for a 1500 kg battery, the use of lead-acid battery will not be feasible in terms of weight. The time required to fully charge a lead-acid battery is 12 to 16 hours (average 14 hours) which is longer than the charge time of a lithium-ion battery.[8] The specific power of the lead-acid battery (approximately 180W/kg) is relatively smaller than the lithium-ion battery (250-340W/kg). [9] Therefore, lead-acid batteries have a longer charge time than lithium-ion batteries. In terms of safety, however, lead acid batteries cause about 2,300 injuries nationally due to acid burns after an explosion or from the lifting and dropping of the battery.[10]

Lithium ion batteries are the most feasible energy storage candidate for the Hyperloop system based on our evaluation. Among the varying types of lithium ion batteries, we are interested in the Lithium Iron Phosphate (LFP) battery. Currently, LFP batteries are widely drawing attention for use in power tools as well as in electric vehicles. LFP uses a Li-ion cell with Lithium Iron Phosphate as a cathode material, which results in low internal resistance and good thermal stability.[11] These Lithium-ion batteries have specific energy of 0.10 kWh/kg. Also, the volumetric density of these batteries is 0.06kWh/liter[12]. The discharge efficiency of a lithium-ion battery is approximately 85%. Therefore, assuming that we are using array of 3.2V LFP batteries, the total weight and size of the battery for single capsule will be 2,438kg and 4,063L, respectively. For the safety issues, LFP battery has high thermal stability compared to other families of lithium-ion batteries – it can sustain up to 250 °C before becoming unstable[13]. Typically, due to such high energy density, lithium ion batteries do have ability to burst into flames, but it only happens 2 to 3 times out of millions of usage. Using LFP under control of computers to keep the temperature low, safety issues can be resolved. As far as cost is also concerned, total cost for LFP battery pack required to run 325kW capsule for 45 minutes is \$196,570.[14] For the cost per kWh to maintain the battery, li-ion battery lasts up to 3,000 charge cycles before it reaches 70% of its maximum capacity. Therefore, cost for each charge cycle will be \$0.27/kWh, which is significantly cheaper than the cost of lead-acid battery in terms of cost per kWh of electricity storage.

Using the data acquired from LightSail on compressed air storage, we found that their technology was durable and provided enough power, but did not meet our safety, weight, and cost-effectiveness criteria. LightSail storage units can have pressures up to 3,000 psi (roughly 204 atm), which can be hazardous in the event of a collision or mechanical failure. We estimated that the power output for compressed air storage would be sufficient for the required power output (325 kilowatts). The size of one unit is “about the size of a room”, which we estimated to be 8 x 10 sq. ft.[15]. This value exceeds the size criteria outlined, resulting in a low score on the Pugh matrix. In terms of weight, we found that compressed air storage machines weigh approximately 20 tons (40,000 lbs.). This value exceeds our weight criterion by far, resulting in another low score on the Pugh matrix. Although we were unable to find the cost per storage unit, we found that energy costs were approximately \$1,470 per kilowatt compared to roughly \$2,000 per kilowatt for battery storage. We correspondingly gave a low score on the matrix for cost relative to our battery solutions. Because LightSail technology does not rely on charge cycles, we expect the storage units to last well over two years, meaning durability scores relatively higher than battery solutions. In terms of energy efficiency, compressed air storage can have up to 90% thermodynamic efficiency, but only 70% round-trip efficiency. These efficiencies are comparable to that of lithium-ion and lead-acid batteries, so we gave LightSail an average score for efficiency. Since considerable time is spent heating high-pressure vapor in the compressed air tank, we gave a lower score on charge time.

Isentropic Energy’s PHES technology uses two large containers of packed gravel to heat energy (see Figure 1, Appendix). The hot container warms up to around 500 degrees Celsius, while the cooling container reaches around -160 degrees Celsius. Due to these extreme temperatures, we decided that pumped heat storage was a safety hazard for Hyperloop operation. Although we found PHES to have sufficient power output relative to other solutions, the size, weight, and cost outweighed any potential benefits. Using a figure of what

the storage tanks would look like relative to a human being (see Figure 2, Appendix), we decided that the size and weight of the tanks would exceed that of our battery solutions. Development costs for a 1.5 MW storage unit were $22 million, which exceeds our goal of $150,000 per unit. PHES achieves 72-80% round-trip efficiency, which satisfies our goal for 21% efficiency. Additionally, PHES does not use charge cycles, so we expect the solution to be durable. However, these benefits do not outweigh the fact that this solution is unsafe, heavy, and too large for use in the hyperloop system.

Limitations, Pitfalls, and Alternatives

Our analysis is based purely on research and not on any experimental data that we have acquired first hand. This approach proved to be sufficient for two of our options, lithium ion batteries and lead-acid batteries. These technologies are widely used in a number of applications, like cars, cell phones, and laptops. However, we were unable to find the same amount of quantitative information about LightSail. This is because it is a relatively new technology that has not been tested or used nearly as much as the two types of batteries previously mentioned. LightSail is still in the prototype phase of development, and therefore it is difficult to analyze this option to the extent that we are able to analyze lithium ion and lead-acid batteries. Our current analysis of LightSail may prove to be inaccurate in the future as the compressed air energy storage branch of clean energy is researched and refined further. These issues are also present in our evaluation of Isentropic Energy for similar reasons. Solutions such as zinc-air fuel cells and SustainX compressed air storage were not evaluated due to lack of data for evaluation.

Although lithium ion batteries are our recommended choice for an energy storage device to be used on the hyperloop transportation capsule, these batteries have some pitfalls. Two of the main concerns are the amount of money and resources required to create a lithium ion battery, and the necessity for careful disposal or recycling of expired lithium ion batteries. Lithium resources are limited, and the price of lithium has tripled in the past 10 years [16]. This could present a problem if the hyperloop transportation system is successful and other cities decide to implement it as a part of their infrastructure, as the demand for lithium ion batteries would increase considerably. Our cost analysis of lithium ion batteries projects that the cost will be $196,570, which exceeds our criterion estimated cost of $150,000 for the capsules. Even though we did not meet the cost goal for our chosen technology, lithium ion batteries are still the best choice. Another issue is that the lithium in these batteries is not fully recycled. If they are not recycled or disposed of properly, the cobalt and nickel cathodes are toxic to the environment [17]. When the batteries are recycled properly, the recovery rate of lithium is low [18]. This coupled with the high cost of safe recycling processes means that it is cheaper to produce and purchase new lithium than to acquire it from recycled batteries, which only increases the risk of resource depletion in the future. This is one area where a compressed air energy storage system like LightSail would be preferred over batteries, as air is not a resource that will be depleted. The weight of our lithium ion batteries is 2,400 kg, which is significantly lighter than lead-acid (over 9,000 kg) but also exceeds the weight of batteries outlined in the hyperloop proposal pdf (1,500 kg). However, it is more feasible to have a slightly heavier energy storage device than to redesign the capsule to accommodate a much larger storage device like LightSail or PHES.

Among the alternative energy storage technologies looked at were Lightsail, traditional Lead-acid batteries, and PHES. Lightsail is a form of compressed air energy storage technology, a recent development and very much still under research. The Lightsail technology works by capturing the heat generated from compressing air at extremely high pressures. This heat is conducted into water, much like nuclear power plants and is stored until the energy is needed. However, due to lack of sufficient information and safety issues regarding highly pressurized air, LightSail is not a viable alternative energy storage system at this point. Lead-Acid batteries consist of flat lead plates immersed in sulfuric acid electrolytes. The positive lead plate is covered with a paste of lead dioxide and the negative plate is made of sponge lead. The battery discharged by conduction of electrolytes from the negative plate back to the positive plate and charged by removal of electrons from the positive plate to the negative plate by a charging source. However, lead acid batteries are not as feasible as Lithium-Ion as they have a lower energy density among other factors. Lastly, Isentropic's Pumped Heat Energy Storage technology transforms electrical energy into a temperature difference between two volumes of crushed mineral material. The system can then efficiently recover electricity from that temperature difference. The main drawback of this technology with regard to the Hyperloop capsule is the size.

The mineral material must be stored in a large tank, which cannot be fitted onto the capsule.

Conclusion

From our evaluation of different technologies, we have come to the conclusion that the Lithium-ion batteries will be the best energy storage system for the Hyperloop capsules today. The Lithium Iron Phosphate battery best meets our criteria for the safety, energy output, energy storage, size, and weight for the capsule energy system, despite not meeting weight and cost criteria. However, there are many promising new energy storage technologies being developed today, and the Lithium-ion may not remain the best choice in the future.

Appendix A: Tables and Figures

Weight	0	0	1	0	0	1	1	1	**4**
Size	1	0	1	0	0	1	1	1	**5**
Charge Time	0	0	0	0	0	0	0	0	**0**

Power Output 1 1 1 0 0 1 1 1 **6**

Safety 1 1 1 1 0 1 1 1 **7**

Energy Efficiency 0 0 1 0 0 0 0 0 **1**

Durability 0 0 1 0 0 1 0 0 **2**

Cost 0 0 1 0 0 1 1 0 **3**

Weight 0 0 1 0 0 1 1 1 **4**

Size 1 0 1 0 0 1 1 1 **5**

Charge Time 0 0 0 0 0 0 0 0 **0**

Power Output 1 1 1 0 0 1 1 1 **6**

Safety 1 1 1 1 0 1 1 1 **7**

Energy Efficiency 0 0 1 0 0 0 0 0 **1**

Durability 0 0 1 0 0 1 0 0 **2**

Cost 0 0 1 0 0 1 1 0 **3**

Weight 0 0 1 0 0 1 1 1 **4**

Size 1 0 1 0 0 1 1 1 **5**

Charge Time 0 0 0 0 0 0 0 0 **0**

Power Output 1 1 1 0 0 1 1 1 **6**

Safety 1 1 1 1 0 1 1 1 **7**

Energy Efficiency 0 0 1 0 0 0 0 0 **1**

Durability 0 0 1 0 0 1 0 0 **2**

Cost 0 0 1 0 0 1 1 0 **3**

	Weight	Size	Charge Time	Power Output	Safety	Energy Efficiency	Durability
Weight	0	0	1	0	0	1	1
Size	1	0	1	0	0	1	1
Charge Time	0	0	0	0	0	0	0
Power Output	1	1	1	0	0	1	1
Safety	1	1	1	1	0	1	1
Energy Efficiency	0	0	1	0	0	0	0
Durability	0	0	1	0	0	1	0
Cost	0	0	1	0	0	1	1

Table 1

Table 1. Pairwise Comparison Chart of Design Criteria
Lead Acid
Weighted
Lightsail
Weighted
Lithium Ion
Weighted
PHES
Weighted

Safety
0.1 3 0.3 1 0.1 **4**
0.4 2 0.2

Power Output
0.2 3 0.6 3 0.6 **3**
0.6 2 0.4

Size
0.2 3 0.6 2 0.4 **4**
0.8 1 0.2

Weight
0.2 3 0.6 1 0.2 **5**
1 1 0.2

Cost
0.1 4 0.4 1 0.1 **3**
0.3 1 0.1

Durability
0.1 2 0.2 5 0.5 **3**
0.3 5 0.5

Energy Efficiency
0.05 3 0.15 2 0.1 **4**
0.2 3 0.15

Charge Time
0.05 3 0.15 2 0.1 **4**
0.2 1 0.05

SUM
1
24
3
17
2.1
30
3.8
16
1.8

Lead Acid
Weighted
Lightsail
Weighted
Lithium Ion
Weighted
PHES
Weighted

Safety
0.1 3 0.3 1 0.1 **4**
0.4 2 0.2

Power Output
0.2 3 0.6 3 0.6 **3**
0.6 2 0.4

Size
0.2 3 0.6 2 0.4 **4**
0.8 1 0.2

Weight
0.2 3 0.6 1 0.2 **5**
1 1 0.2

Cost
0.1 4 0.4 1 0.1 **3**
0.3 1 0.1

Durability
0.1 2 0.2 5 0.5 **3**
0.3 5 0.5

Energy Efficiency
0.05 3 0.15 2 0.1 **4**
0.2 3 0.15

Charge Time
0.05 3 0.15 2 0.1 **4**
0.2 1 0.05

SUM
1
24
3
17
2.1
30
3.8
16
1.8

Lead Acid
Weighted
Lightsail
Weighted

Lithium Ion
Weighted
PHES
Weighted

Safety
0.1 3 0.3 1 0.1 **4**
0.4 2 0.2

Power Output
0.2 3 0.6 3 0.6 **3**
0.6 2 0.4

Size
0.2 3 0.6 2 0.4 **4**
0.8 1 0.2

Weight
0.2 3 0.6 1 0.2 **5**

1 1 0.2

Cost
0.1 4 0.4 1 0.1 **3**
0.3 1 0.1

Durability
0.1 2 0.2 5 0.5 **3**
0.3 5 0.5

Energy Efficiency
0.05 3 0.15 2 0.1 **4**
0.2 3 0.15

Charge Time
0.05 3 0.15 2 0.1 **4**
0.2 1 0.05

SUM
1
24
3
17
2.1
30
3.8
16
1.8

	Weight	Lead Acid	Weighted	Lightsail	Weighted	Lithium Ion	Weighted
Safety	0.1	3	0.3	1	0.1	**4**	0.4
Power Output	0.2	3	0.6	3	0.6	**3**	0.6
Size	0.2	3	0.6	2	0.4	**4**	0.8
Weight	0.2	3	0.6	1	0.2	**5**	1
Cost	0.1	4	0.4	1	0.1	**3**	0.3
Durability	0.1	2	0.2	5	0.5	**3**	0.3
Energy Efficiency	0.05	3	0.15	2	0.1	**4**	0.2
Charge Time	0.05	3	0.15	2	0.1	**4**	0.2
SUM	**1**	**24**	**3**	**17**	**2.1**	**30**	**3.8**

Table 2

Table 2. Pugh Scoring Matrix

Figure 1

Table 3. Final Pugh Scoring Matrix

Figure 2

Figure 1: Diagram of PHES Process[19]

Figure 3

Figure 2: PHES storage tanks relative to the size of a human[19]

Image not finished

Figure 4

Figure 3: LightSail Prototype[20]

Appendix B: Calculations

[14] Calculation for Lithium-ion battery

1 3.2V 130Ah LiFePO4 battery is sold for $200 in current market. Thus, the total energy E for battery is:

E = 3.2V * 130Ah = 416Wh = 0.416 kWh

And, the battery discharge efficiency is 85%, so 85 percent of stored energy can be used:

E = 0.416kWh * 0.85 = 0.354kWh

Also, after 3,000 cycles of usage, the maximum capacity of battery will drop to 70%. Therefore, for each trip we should assume that we only use 70% of its maximum capacity.

E = 0.354kWh * 0.7 = 0.248kWh

The total energy required for a single run of capsule is:

E_tot = 325kW*45/60hr = 243.75 kWh

Thus, the cost of the battery will be:

Cost = ($200/0.248kWh) * 243.75kWh = $196,570

Also, the cost per kWh of energy for each charge cycle will be:

Cost' = ($200/0.248kWh)/(3,000 cycles) = $0.27/kWh per charge cycle

[7] Calculation for Lead-acid battery

Cost per battery scaling up from a Power-Sonic PS-1270 (12V 7ah) lead-acid battery

243.75kWh/(12V*7Ah*0.001kWh/Wh*80%*80%)*$15=$68,011

Energy cost per kWh after taking account of durability

$15/(12V*7Ah*300*0.001kWh/Wh*80%*80%)=$0.93/kWh

Minimum weight of lead-acid battery to have the required energy storage

243.75kWh*1000Wh/kWh/(40Wh/kg*80%*80%)=9521 kg

Minimum volume of lead-acid battery to have the required energy storage

243.75kWh*1000Wh/kWh/(87.5Wh/L*80%*80%)*0.001L/m^3= 4.35 m^3

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